Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Review about the current dynamical core developments in the COSMO model

35th EWGLAM / 20th SRNWP meeting
30 Sept. – 03 Oct. 2013, Antalya

Michael Baldauf, Ulrich Blahak (Deutscher Wetterdienst),
Zbigniew Piotrowski (IMGW, Poland)

Dynamical core (Euler solver) developments in COSMO

- Current Runge-Kutta dynamical core
  (*Wicker, Skamarock (2002) MWR, Baldauf (2010) MWR*)
  - further maintenance (DWD) (~0.5 FTE)
  - higher order discretizations (Univ. Cottbus) (~1 FTE)

COSMO priority project ‚Conservative dynamical core' (2008-2012):

(Baldauf et al. (2013) COSMO Tech. Rep.no.23, available soon)

- EULAG (anelastic) as a candidate for the future COSMO dyn. core

  Ziemiański et al. (2011) Acta Geophysica
  Rosa et al. (2011) Acta Geophysica
  Kurowski et al. (2011) Acta Geophysica

  → follow up PP ‚COSMO-EULAG operationalization' (2012-2015) (IMGW, Poland) (~3 FTE)
- fully implicit FV solver ‚CONSOL' (CIRA, Italy) (~0.5 FTE)
  Jameson (1991) AIAA

Project in the framework of the German research foundation

- Dynamical core based on Discontinuous Galerkin methods
  (DWD, Univ. Freiburg) (~1.08 FTE)

MetStröm

1 FTE (full time equivalent) = 1 person/year

The new fast waves solver for the COSMO Runge-Kutta dynamical core:

M. Baldauf (DWD)

Main changes towards the old fast waves solver:

1. improvement of the vertical discretization:
   use of weighted averaging operators for all vertical operations
2. divergence in strong conservation form
3. optional: complete 3D (=isotropic) divergence damping
4. optional: Mahrer (1984) discretization of horizontal pressure gradients

overall goal: improve numerical stability of COSMO

- new fast waves solver is available since COSMO 4.24
- runs operationally in COSMO-DE, -DE-EPS, -EU at DWD
  since 16 Jan. 2013

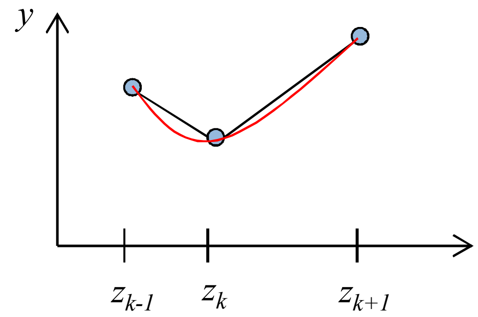
M. Baldauf (2013) COSMO Technical report No. 21 (www.cosmo-model.org)

Discretization in stretched grids

Example: calculate 1st derivative $\partial y/\partial z$ by an (at most) 3-point formula
(← tridiagonal solver)

Approach 1: by weightings in ‚original space'

$$\left.\frac{dy}{dz}\right|_{z_k} = \frac{z_{k+1}-z_k}{z_{k+1}-z_{k-1}} \cdot \frac{y_k - y_{k-1}}{z_k - z_{k-1}} + \frac{z_k - z_{k-1}}{z_{k+1}-z_{k-1}} \cdot \frac{y_{k+1}-y_k}{z_{k+1}-z_k}$$



(e.g. *Ikeda, Durbin (2004) JCP*)

Approach 2: use of a coordinate transformation $z_k = f(\zeta_k)$, $\zeta_k = k\,\Delta\zeta$

$$\frac{\partial y}{\partial z} = \frac{\partial \zeta}{\partial z}\,\frac{\partial y}{\partial \zeta}$$

centered diff.

straightforward in unstaggered A-grid,
less clear in staggered C-grid

Improvement of the vertical discretization

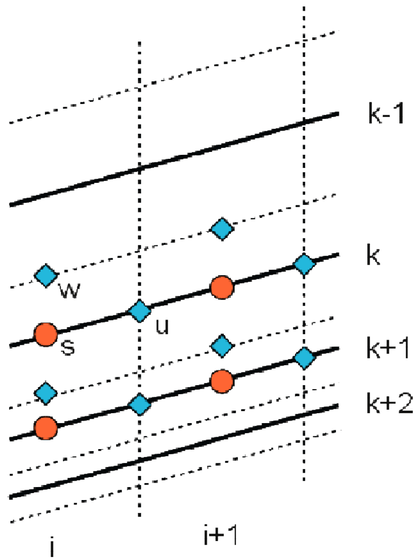
COSMO: *Half levels* (w-positions) are defined by a stretching function $z_k = f(\zeta_k)$;
Main levels (p', T'-pos.) lie in the middle of two half levels

Arithmetic average from half levels to main level:

$$\overline{\psi}^{\zeta} \equiv A_\zeta \psi|_{i,j,k} := \frac{1}{2}(\psi_{i,j,k-\frac{1}{2}} + \psi_{i,j,k+\frac{1}{2}})$$

Weighted average from main levels to half level

$$\overline{\psi}^{\zeta,N} \equiv A_\zeta^N \psi|_{i,j,k-\frac{1}{2}} := g_{k-\frac{1}{2}}\psi_{i,j,k} + (1-g_{k-\frac{1}{2}})\psi_{i,j,k-1}$$



Derivatives always by centered differences (appropriate average used before)

$$\delta_\zeta \psi|_{i,j,k} := \frac{\psi_{i,j,k+\frac{1}{2}} - \psi_{i,j,k-\frac{1}{2}}}{\Delta\zeta}$$

G. Zängl could show the advantages of weighted averages in the explicit parts of the fast waves solver.
New: application to all vertical operations (also the implicit ones)

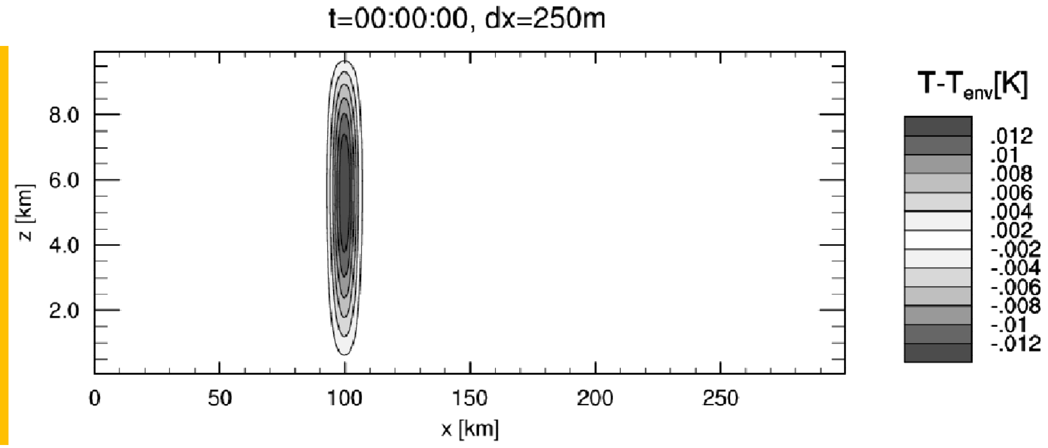
How can we check the correctness of these vertical weightings?

Compare against:

An analytic solution for linear gravity waves in a channel as a test case for solvers of the non-hydrostatic, compressible Euler equations

Baldauf, Brdar (2013) QJRMS

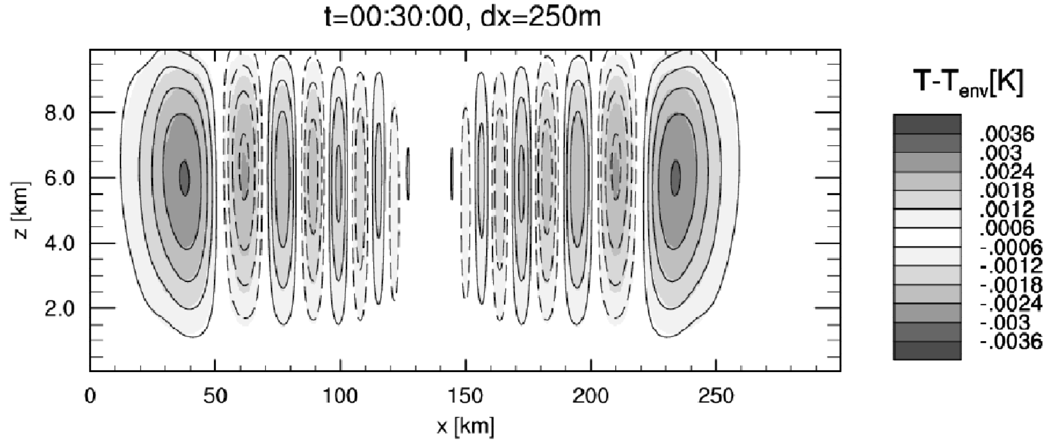
Analytic solution for the expansion of sound / gravity waves in an isothermal atmosphere for the *non-hydrostatic, compressible Euler equations* available *(Baldauf, Brdar (2013) QJRMS)*



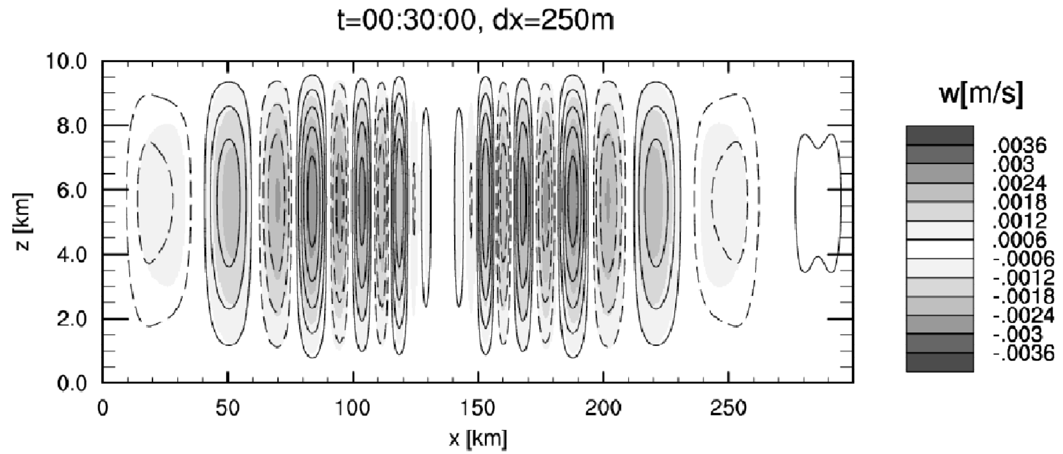
Initialization similar to
Skamarock, Klemp (1994)

$$T'(x,z,t=0) = \Delta T \cdot e^{\frac{1}{2}\delta z} \cdot e^{-\frac{(x-x_c)^2}{d^2}} \cdot \sin \pi \frac{z}{H}$$

$$p'(x,z,t=0) = 0$$



Small scale test
with a basic flow U_0=20 m/s
f=0



Black lines: analytic solution
Shaded: COSMO-simul.

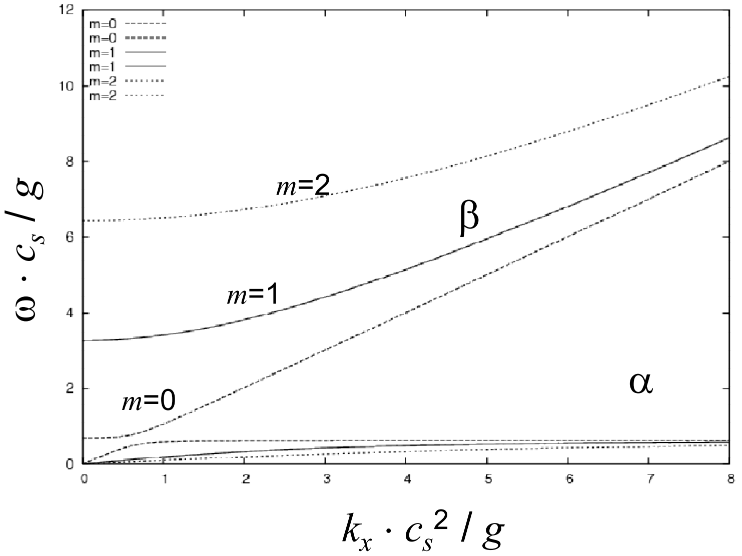
Bretherton-, Fourier- and Laplace-Transformation →

Analytic solution for the Fourier transformed vertical velocity w

$$\hat{w}_b(k_x, k_z, t) = -\frac{1}{\beta^2 - \alpha^2} \left[-\alpha \sin \alpha t + \beta \sin \beta t + (f^2 + c_s^2 k_x^2) \left(\frac{1}{\alpha} \sin \alpha t - \frac{1}{\beta} \sin \beta t \right) \right] g \frac{\hat{\rho}_b(k_x, k_z, t=0)}{\rho_s}$$

analogous expressions for $u_b(k_x, k_z, t)$, ...

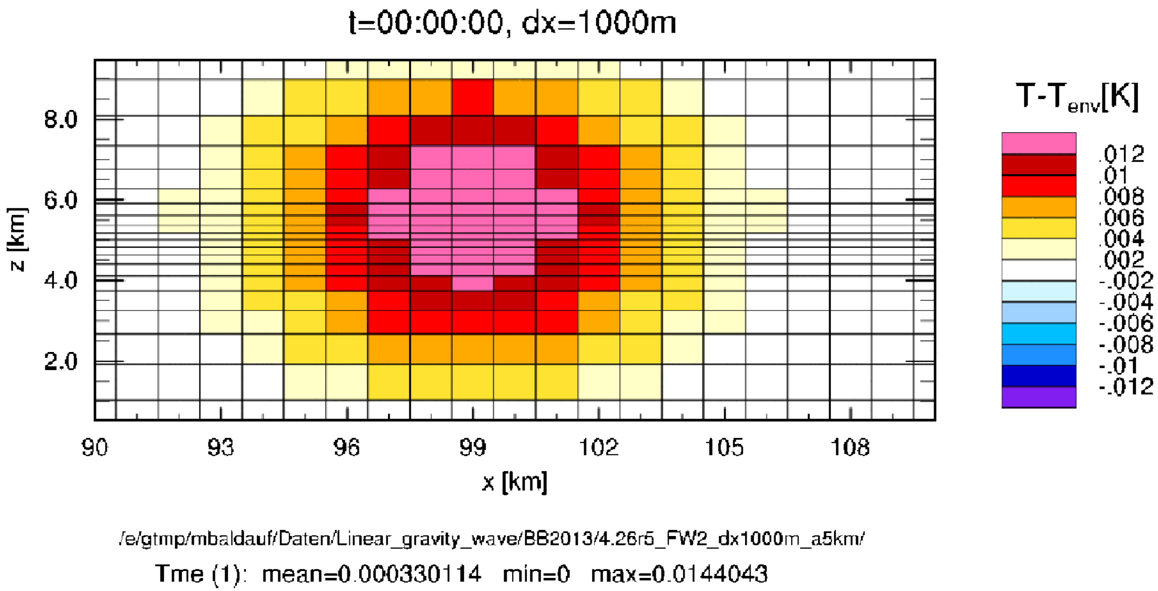
The frequencies α, β are the gravity wave and acoustic branch, respectively, of the dispersion relation for compressible waves in a channel with height H;
$k_z = (\pi / H) \cdot m$

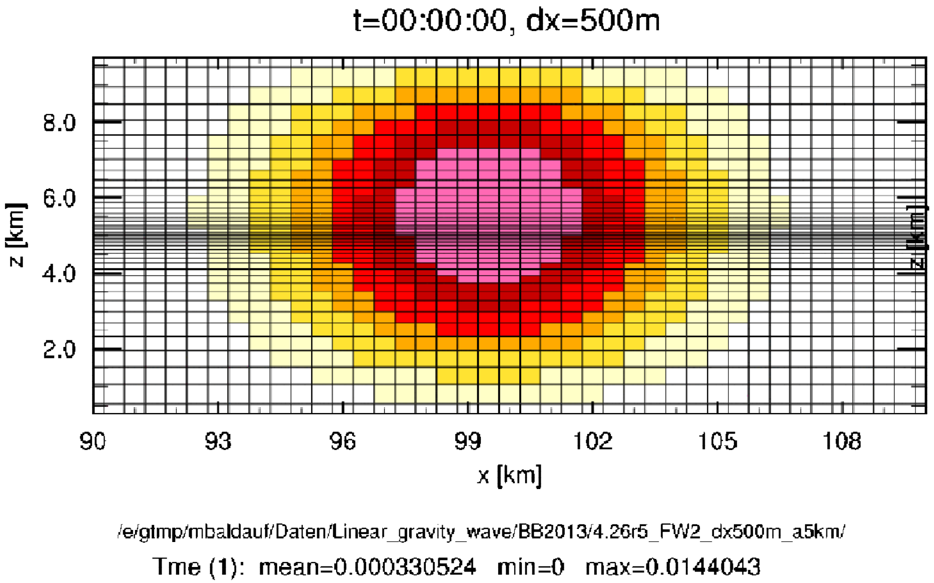


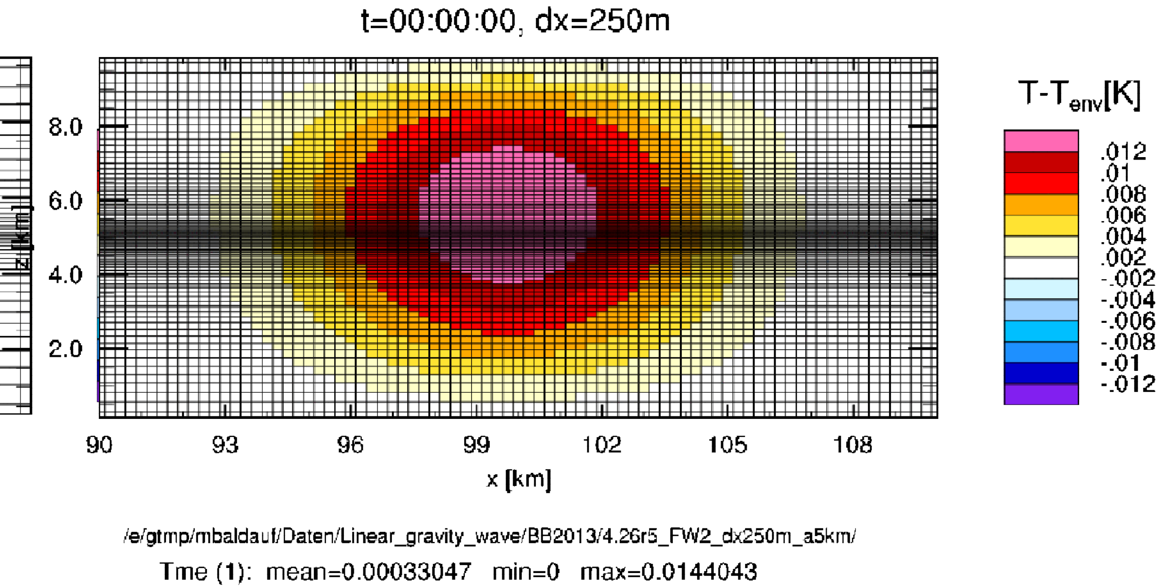
Baldauf, Brdar (2013) QJRMS

Convergence test with vertically stretched grid

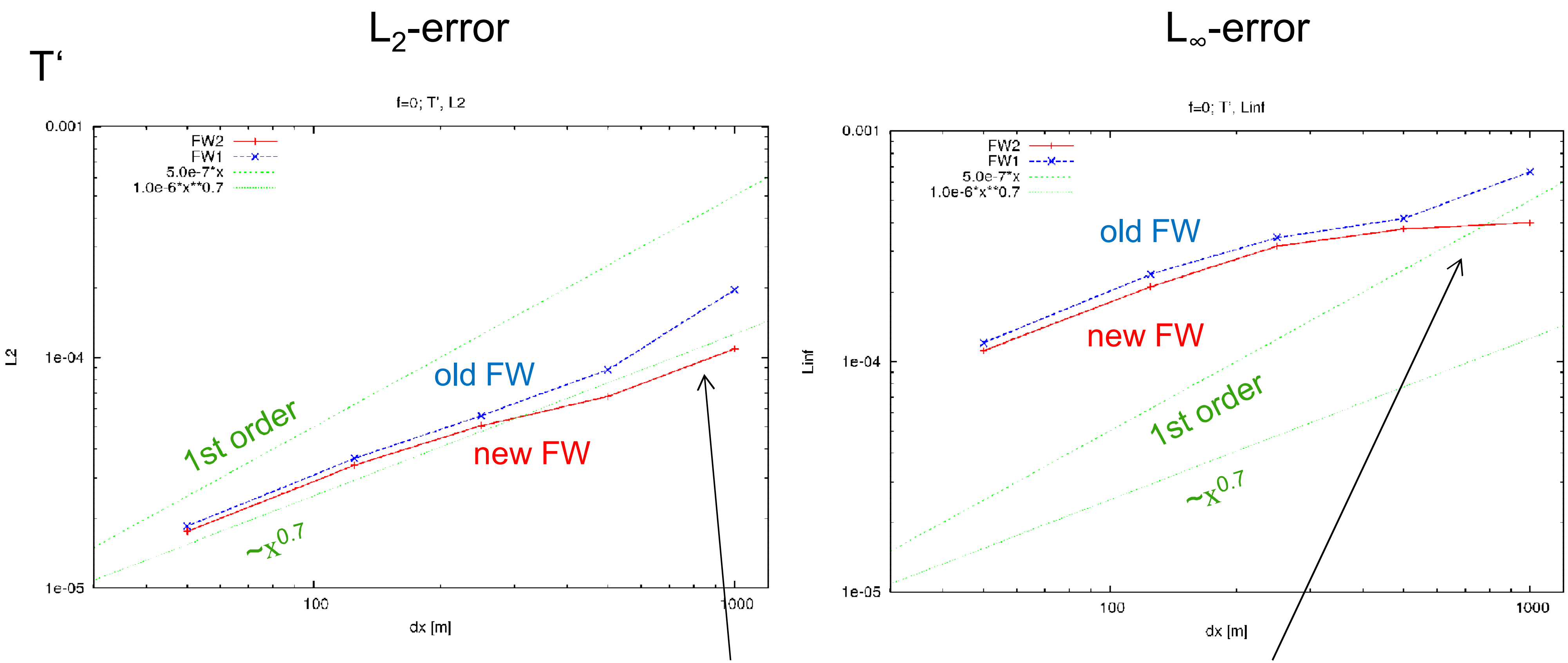
initial condition for T'
and grids
for the first 3 resolutions







Convergence test with vertically stretched grid for old and new fast waves solver



the improvement is best for coarse resolutions, because here the highest relative stretching for neighbouring grid boxes occurs

Bug fix in the water loading contribution of the buoyancy term

$$\frac{\partial w}{\partial t} + \mathbf{v} \cdot \nabla w = -\frac{1}{\rho}\frac{\partial p'}{\partial z} + \underbrace{g \left(\frac{p_0}{p}\frac{T'}{T_0} - \frac{p'}{p} + \frac{p_0}{p}\frac{T}{T_0} q_x \right)}_{-g\frac{\rho'}{\rho}} + \ldots$$

Moisture correction in ideal gas law:
(water loading)

$$q_x := \left(\frac{R_v}{R_d} - 1 \right) q_v - q_c - q_r - \ldots$$

RK-scheme with new fast waves solver:

4.27: moisture variables q_v, q_c, … in q_x at timelevel `nnew`

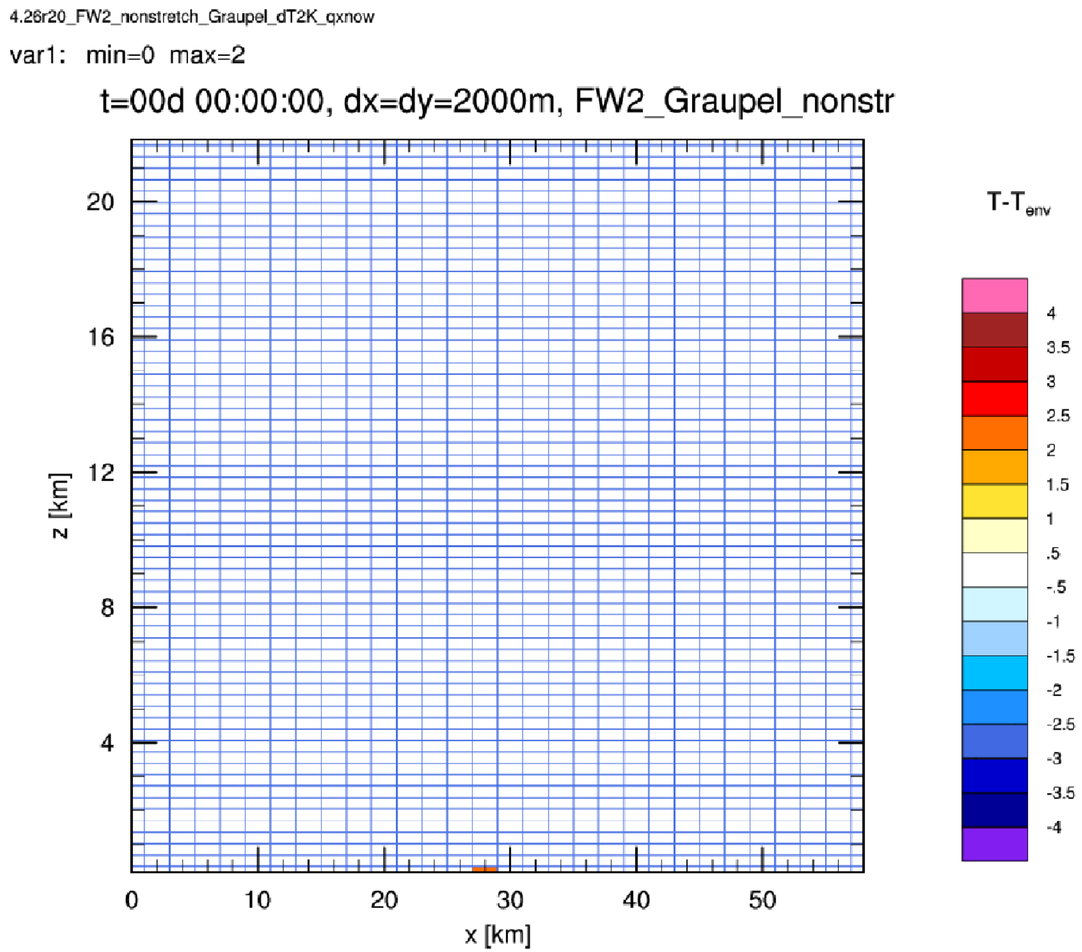
4.28: moisture variables q_v, q_c, … in q_x at timelevel `nnow`

reason: during the RK-scheme `nnew` still means ‚*old*' for the moisture variables!

This bug fix is important in strongly convective situations

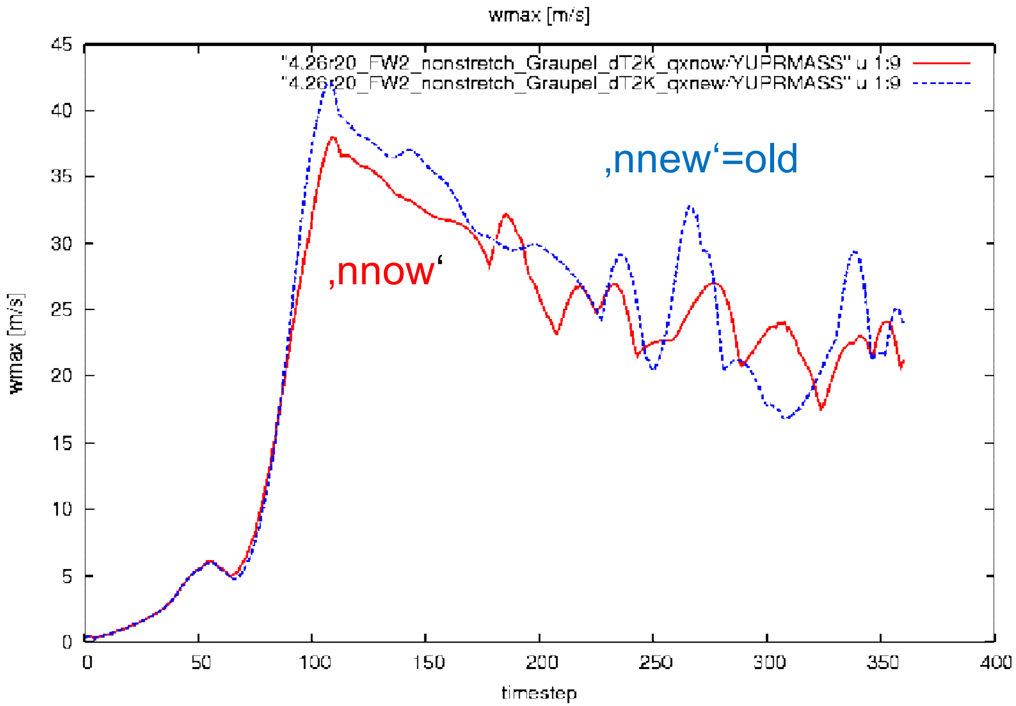
Idealised convection test at the resolution limit of the model

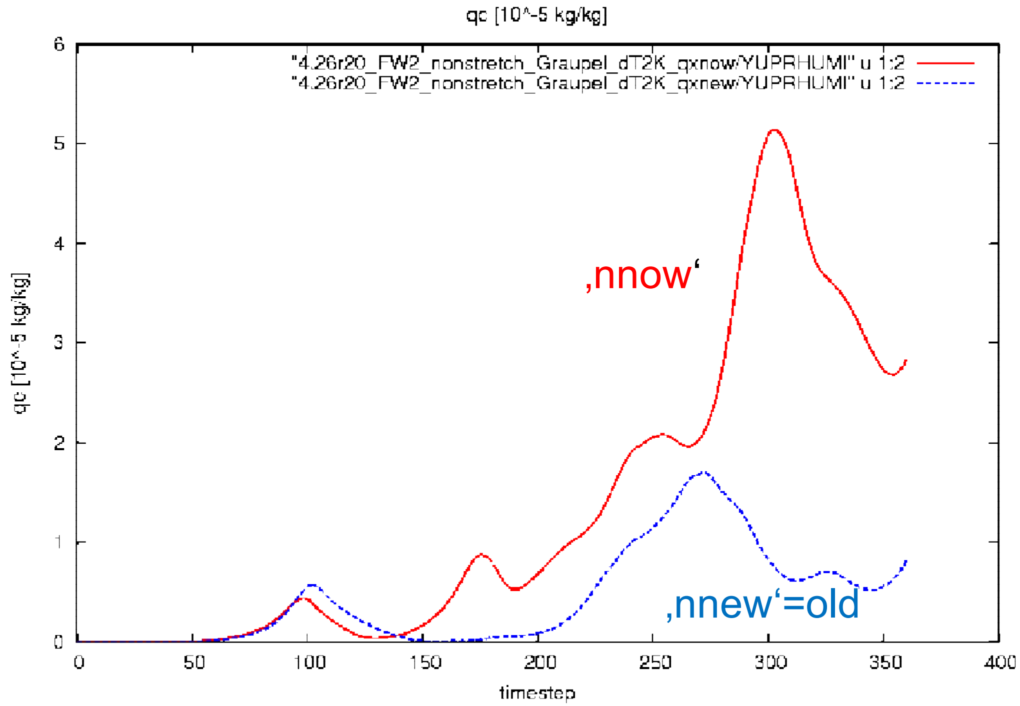
- T-perturbation ∆T=+2K in only **one** grid box (in z~500m)
- Stratification analogous to Weismann, Klemp (1982) MWR
- Atmosphere at rest
- No turbulence, only cloud physics
- Non-stretched grid



Idealised convection test at the resolution limit of the model

w_{max} [m/s] | cloud water q_c [0.01 g/kg]



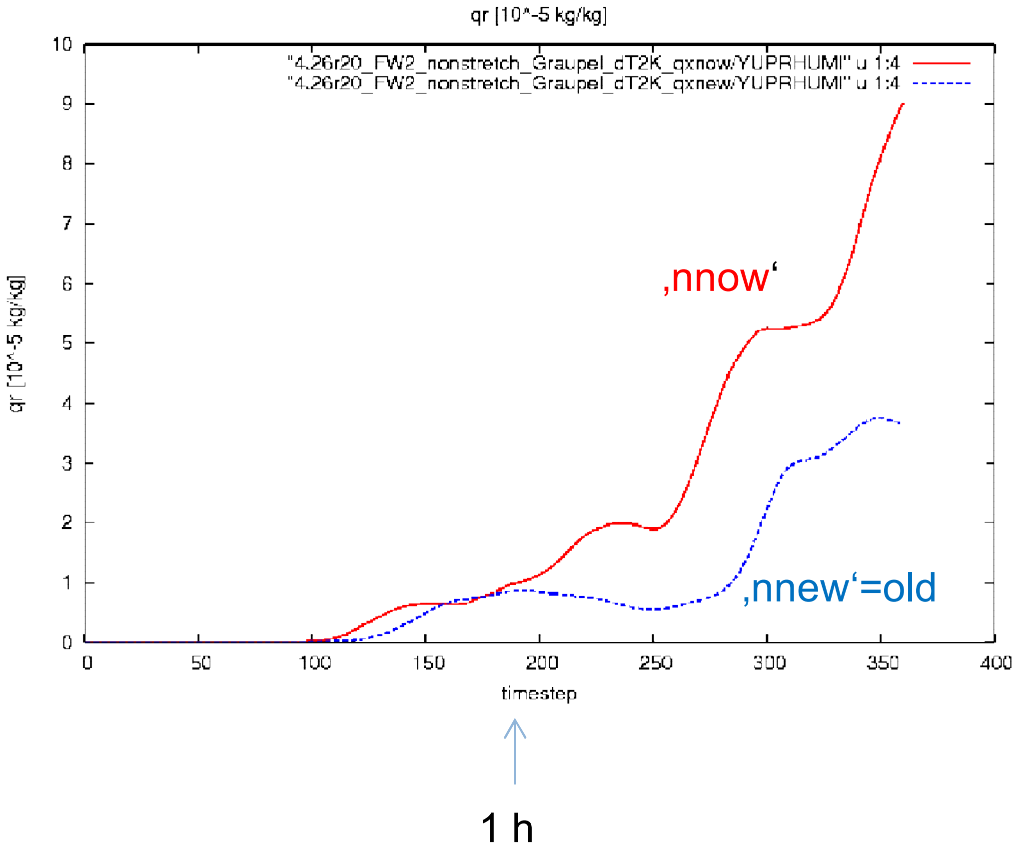


1 h | 1 h

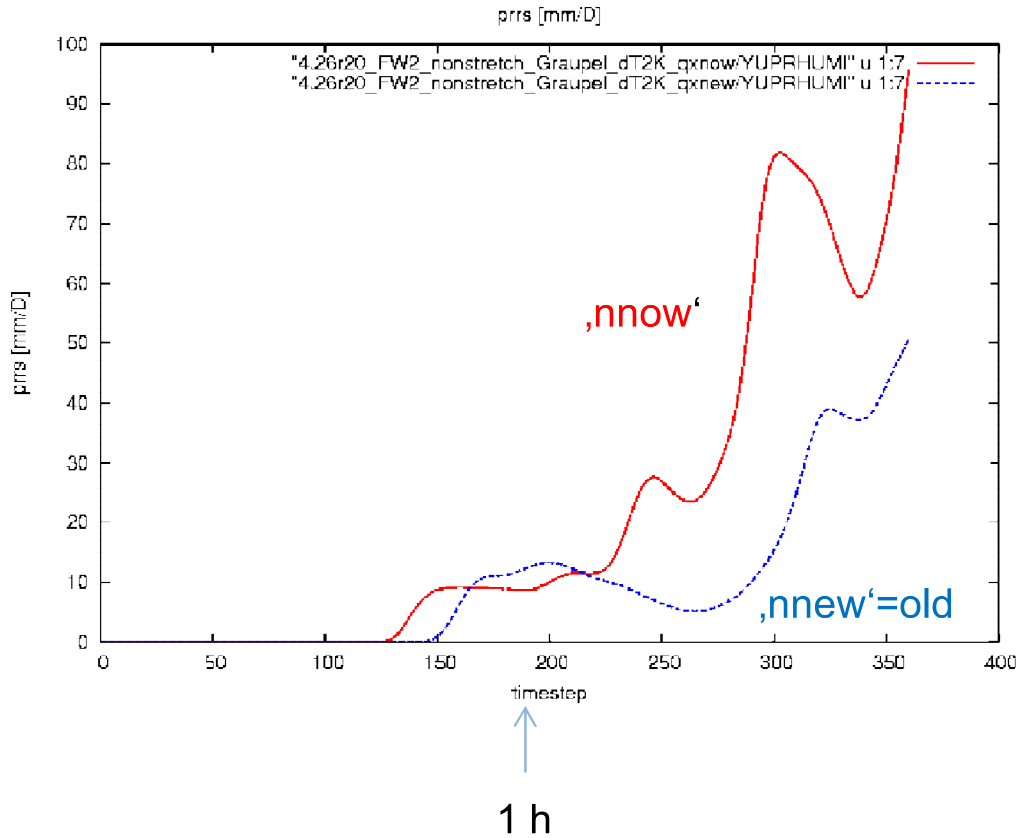
graupel-scheme used (q_v , q_c , q_i, q_r , q_s , q_g)

Idealised convection test at the resolution limit of the model

rain q_r [0.01 g/kg]



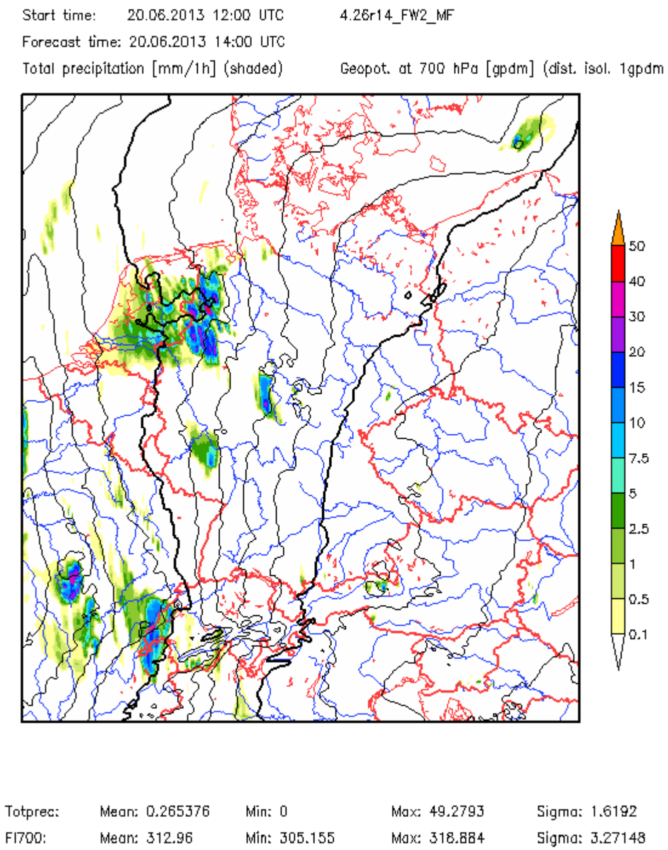
precipitation rate [mm/day]



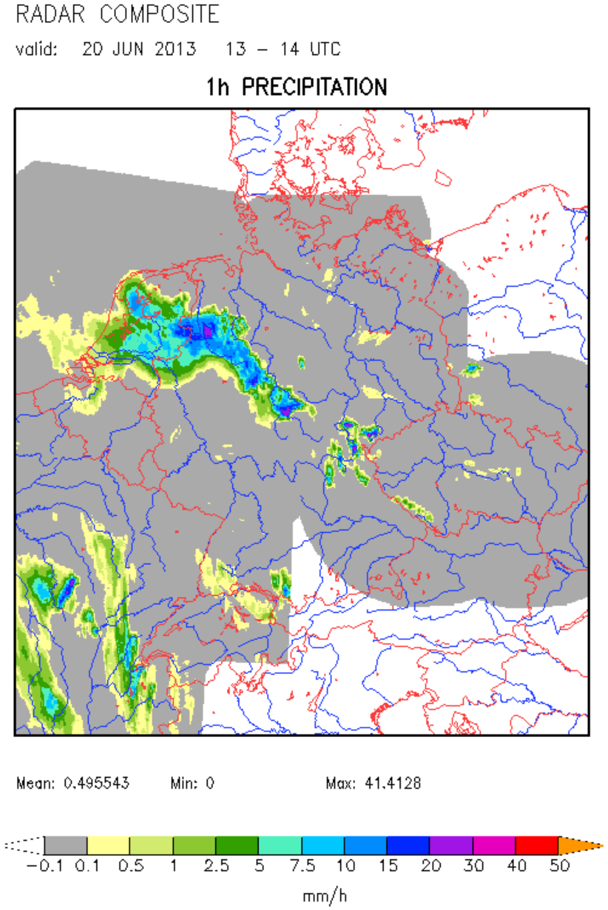
graupel-scheme used (q_v , q_c , q_i, q_r , q_s , q_g)

COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

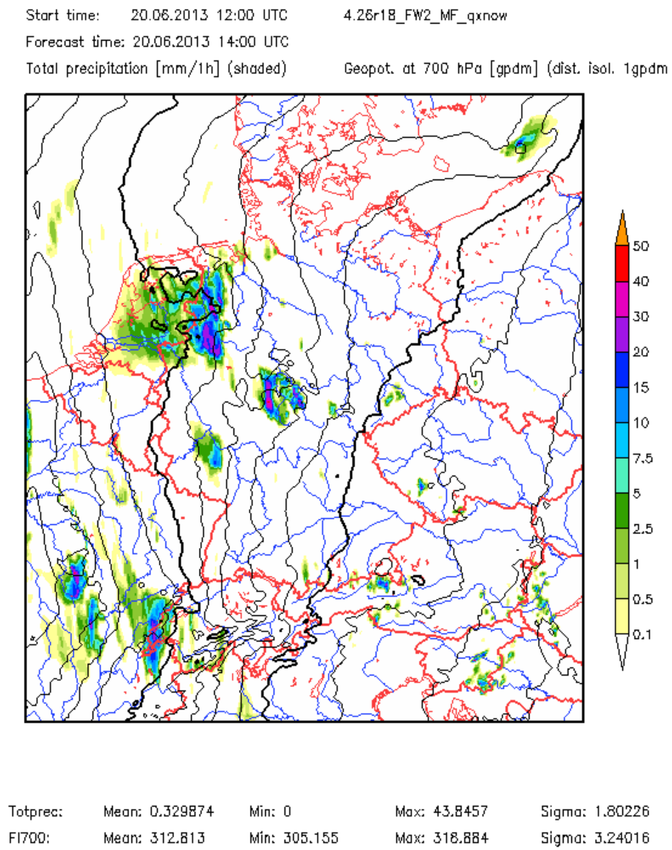
‚nnew'



Radar



‚nnow'



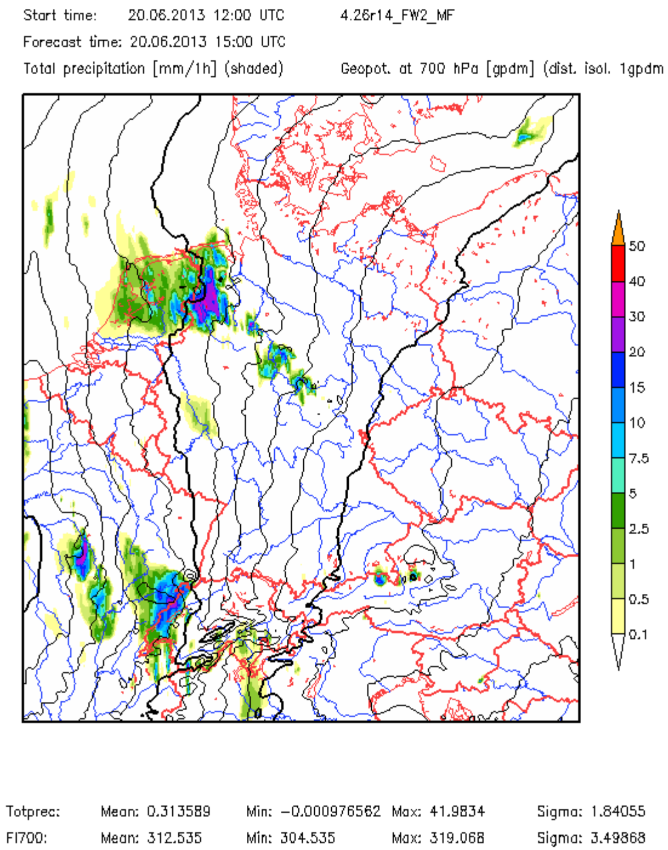
Front coming in at evening;
convergence line during afternoon with heavy precipitation

COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

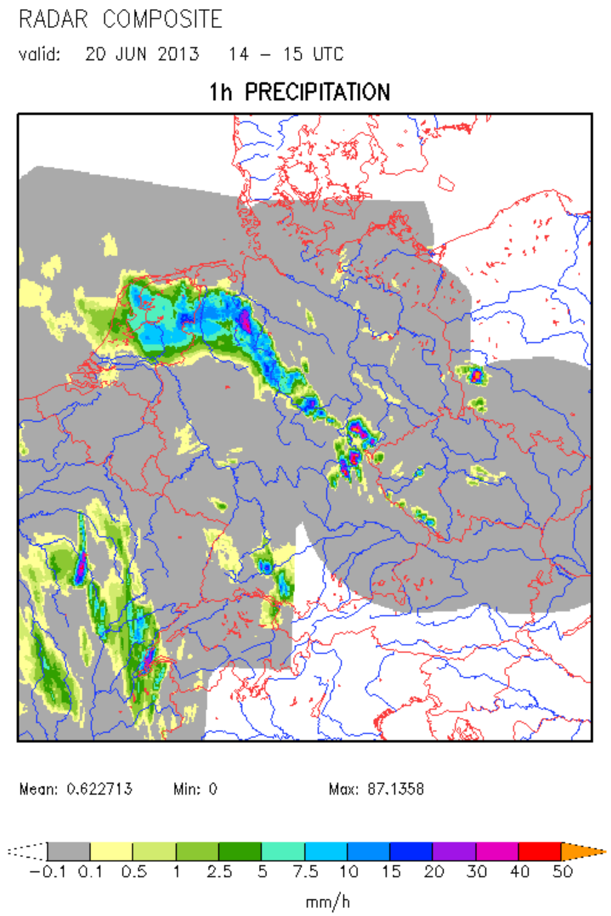
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

DWD

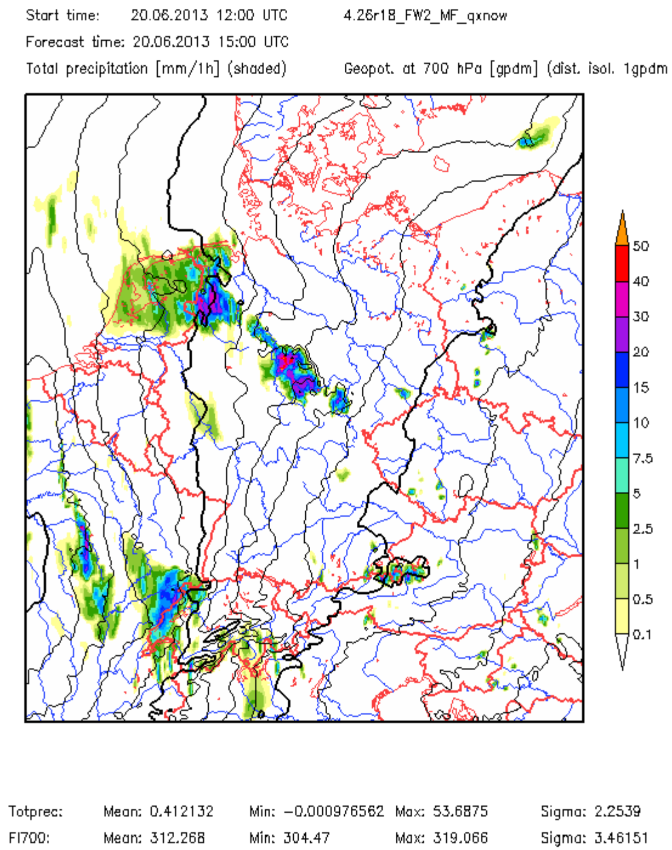
‚nnew‘



Radar



‚nnow‘

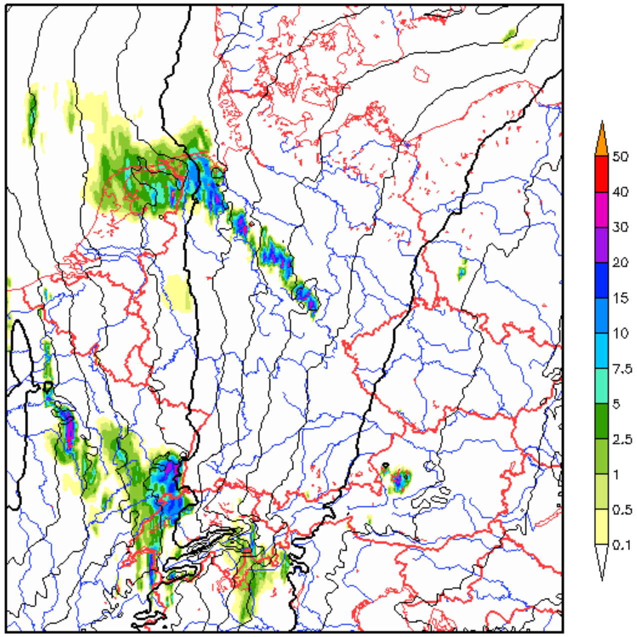


COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

‚nnew‘

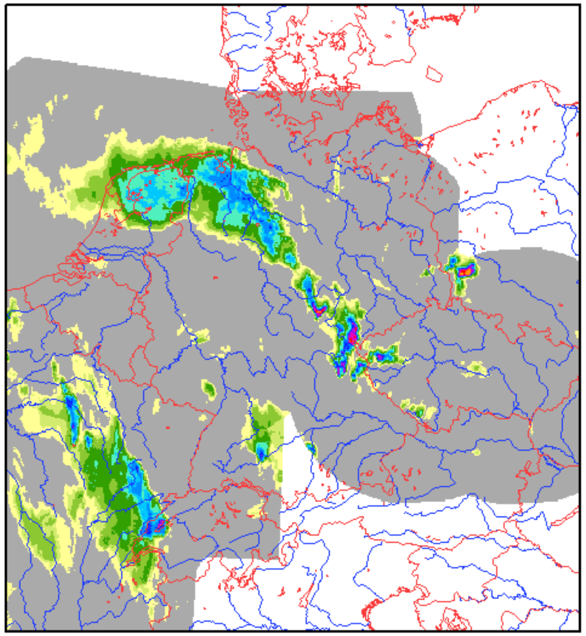
Start time: 20.06.2013 12:00 UTC   4.26r14_FW2_MF
Forecast time: 20.06.2013 16:00 UTC
Total precipitation [mm/1h] (shaded)   Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



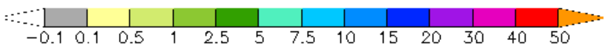
Totprec: Mean: 0.348036 Min: 0 Max: 70.5938 Sigma: 1.913
FI700: Mean: 312.133 Min: 304.403 Max: 318.77 Sigma: 3.50543

Radar

RADAR COMPOSITE
valid: 20 JUN 2013 15 – 16 UTC
1h PRECIPITATION

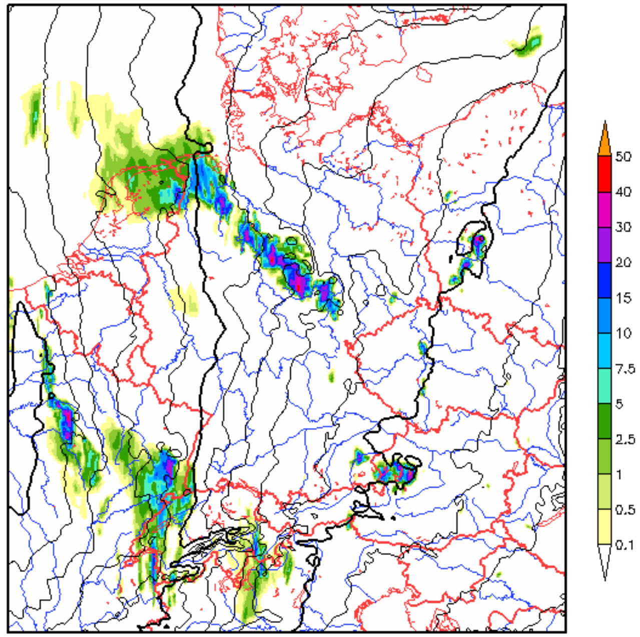


Mean: 0.658538 Min: 0 Max: 95.7285



‚nnow‘

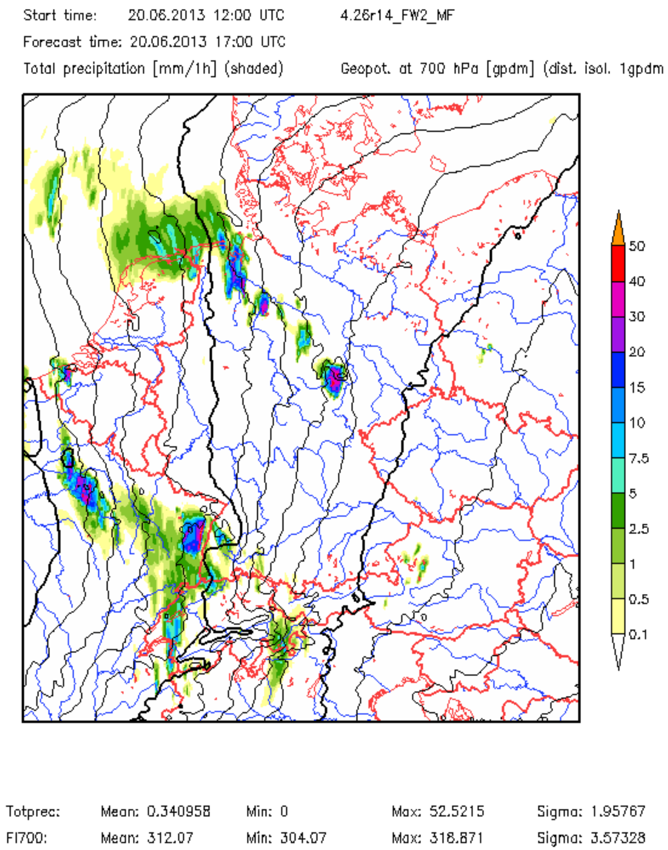
Start time: 20.06.2013 12:00 UTC   4.26r18_FW2_MF_qxnow
Forecast time: 20.06.2013 16:00 UTC
Total precipitation [mm/1h] (shaded)   Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



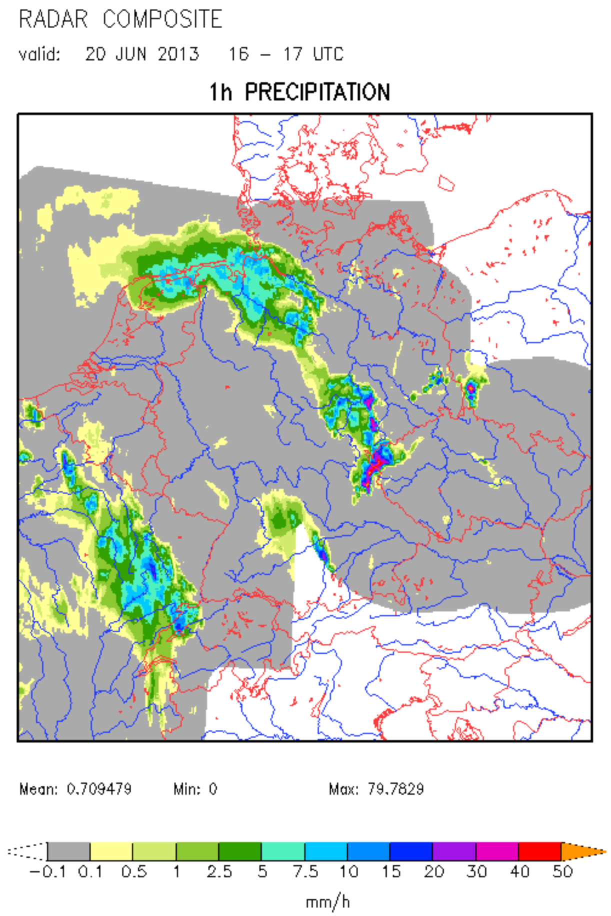
Totprec: Mean: 0.441332 Min: 0 Max: 48.793 Sigma: 2.25112
FI700: Mean: 311.809 Min: 304.316 Max: 318.77 Sigma: 3.47157

COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

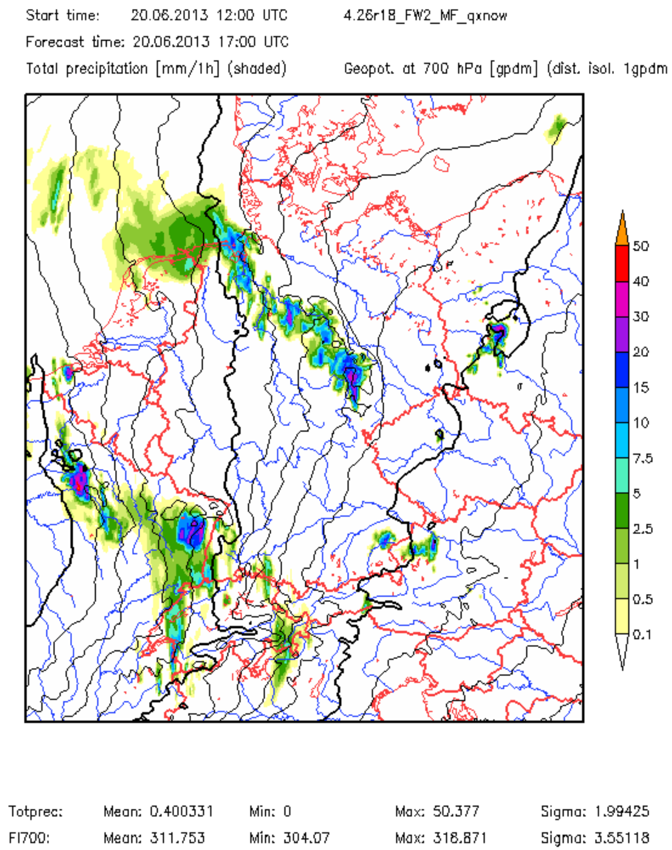
‚nnew‘



Radar



‚nnow‘



COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

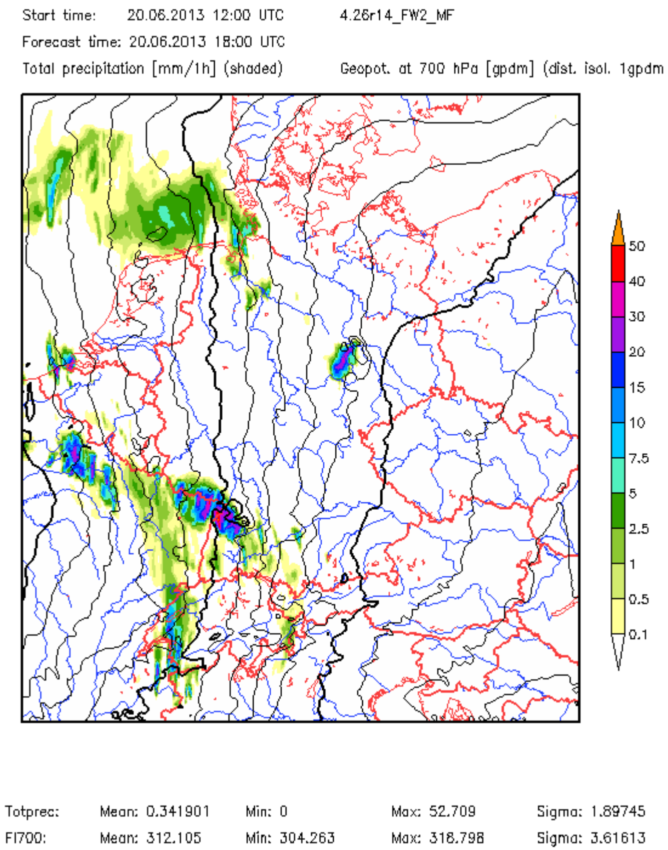
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

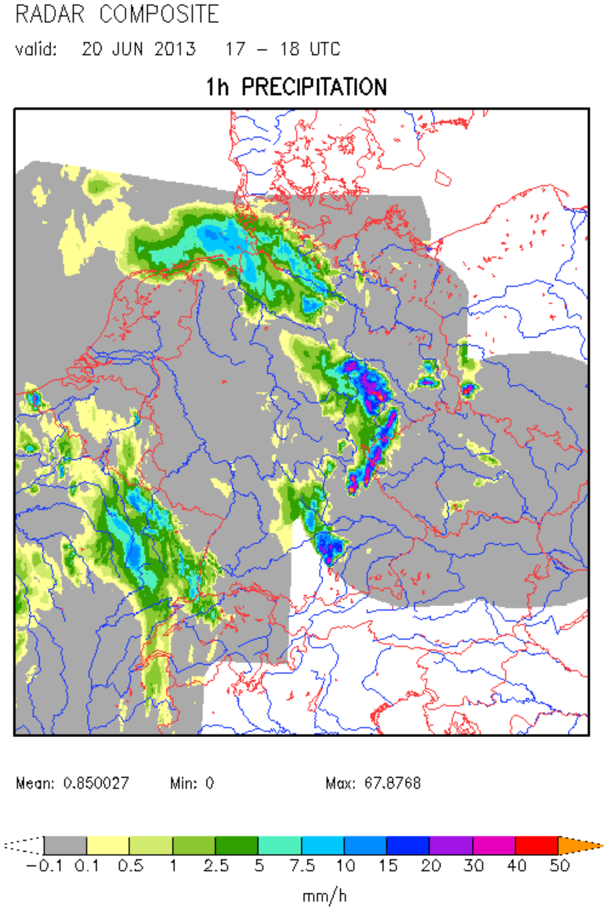
DWD

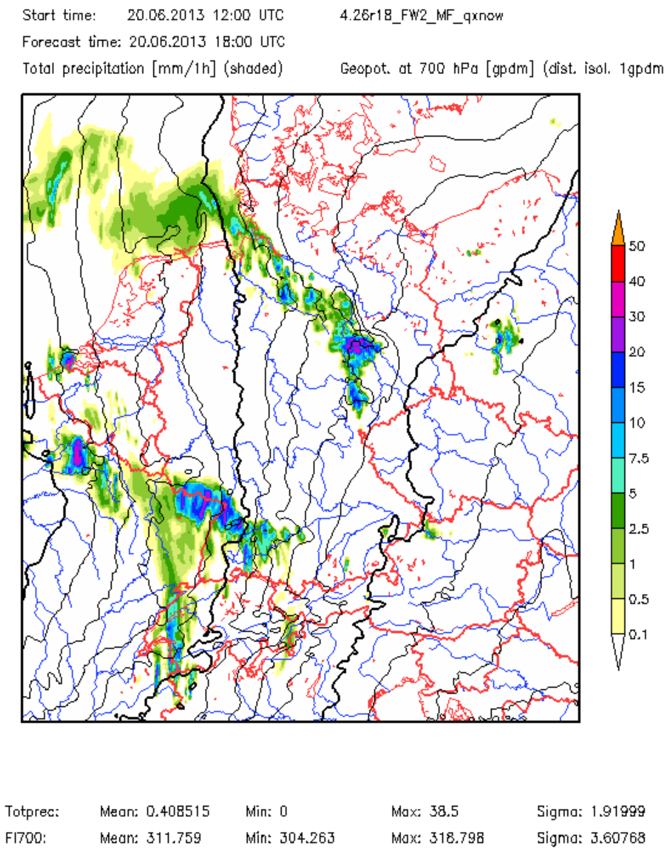
,nnew'

Radar

,nnow'





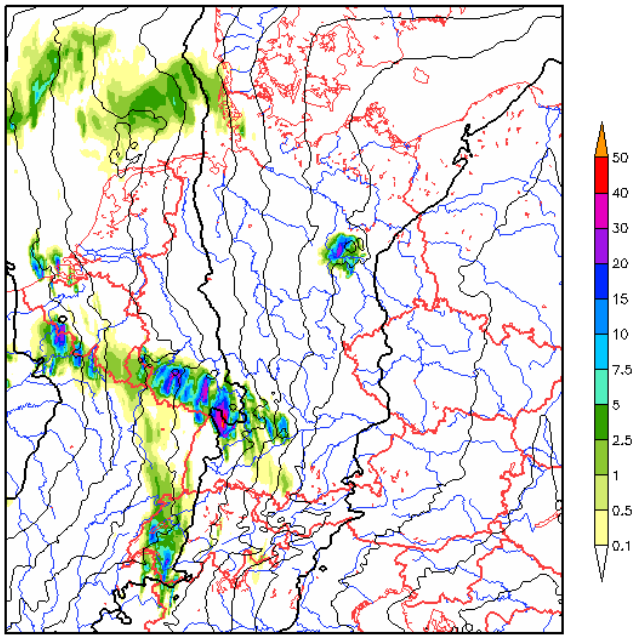


COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

‚nnew‘

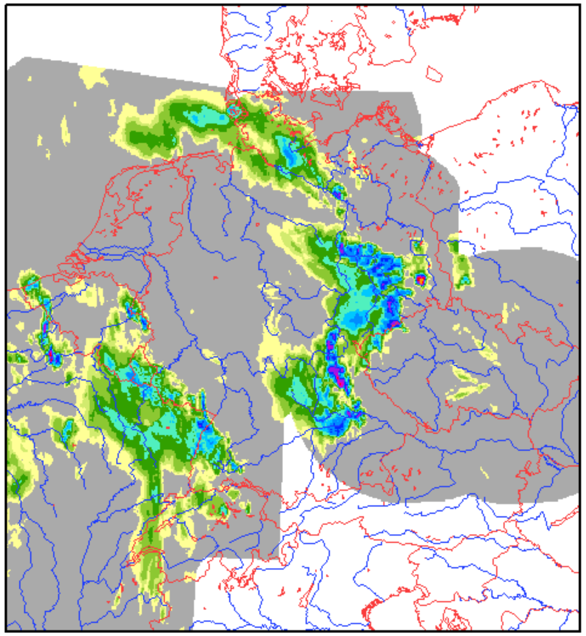
Start time: 20.06.2013 12:00 UTC   4.26r14_FW2_MF
Forecast time: 20.06.2013 19:00 UTC
Total precipitation [mm/1h] (shaded)   Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



Totprec: Mean: 0.341206 Min: 0 Max: 56.2754 Sigma: 1.83598
FI700: Mean: 312.012 Min: 304.108 Max: 318.866 Sigma: 3.71331

Radar

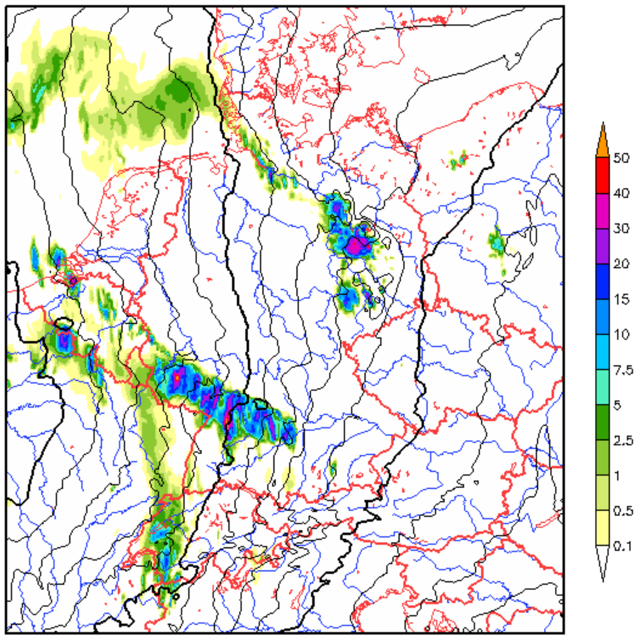
RADAR COMPOSITE
valid: 20 JUN 2013 18 – 19 UTC
1h PRECIPITATION



Mean: 0.850653 Min: 0 Max: 76.6488

‚nnow‘

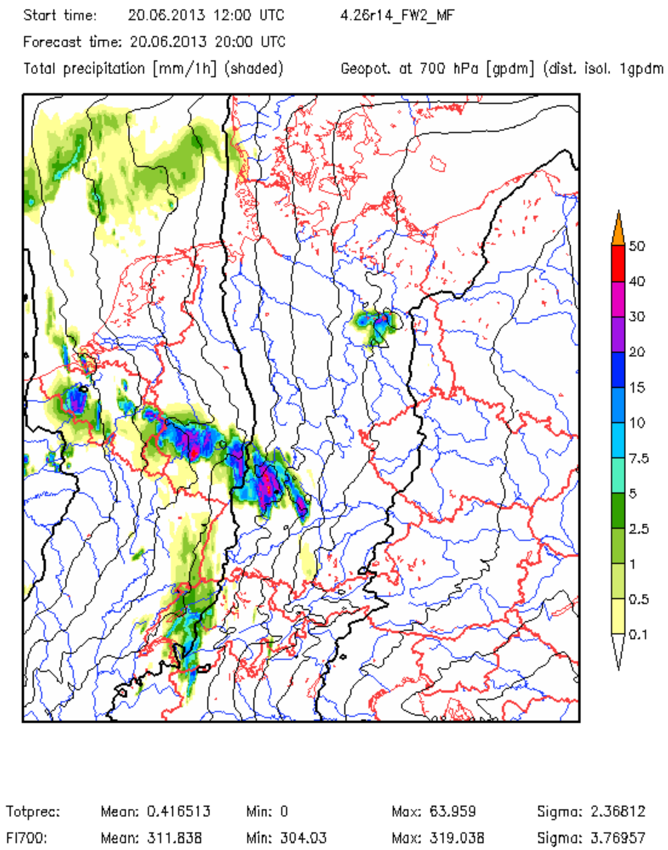
Start time: 20.06.2013 12:00 UTC   4.26r18_FW2_MF_qxnow
Forecast time: 20.06.2013 19:00 UTC
Total precipitation [mm/1h] (shaded)   Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



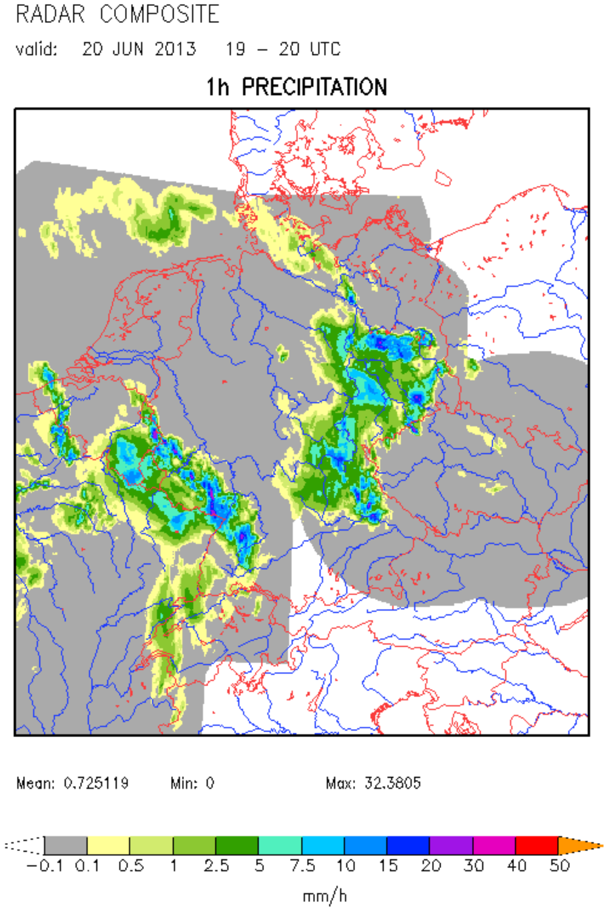
Totprec: Mean: 0.475635 Min: 0 Max: 57.1387 Sigma: 2.42674
FI700: Mean: 311.594 Min: 304.09 Max: 318.866 Sigma: 3.71939

COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

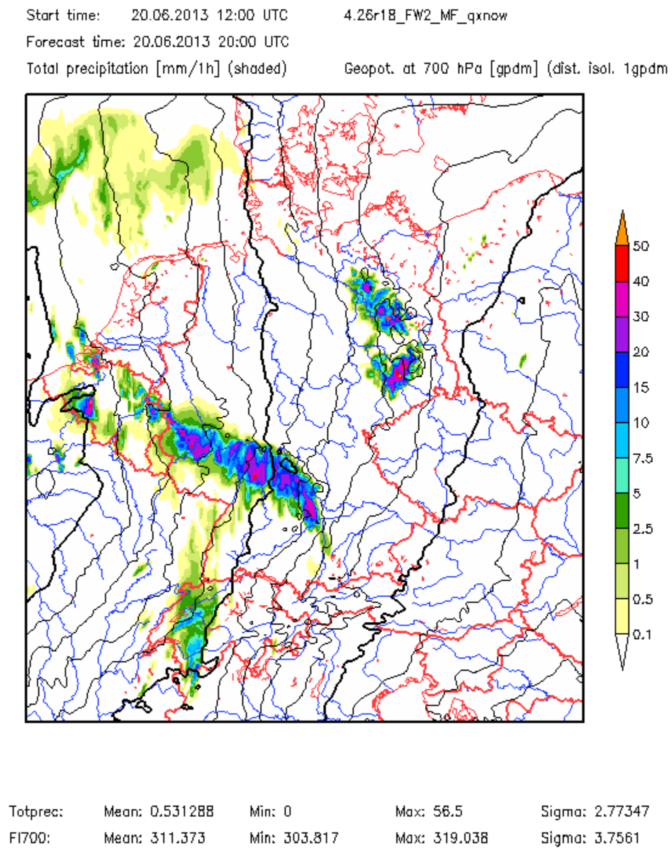
‚nnew‘



Radar



‚nnow‘

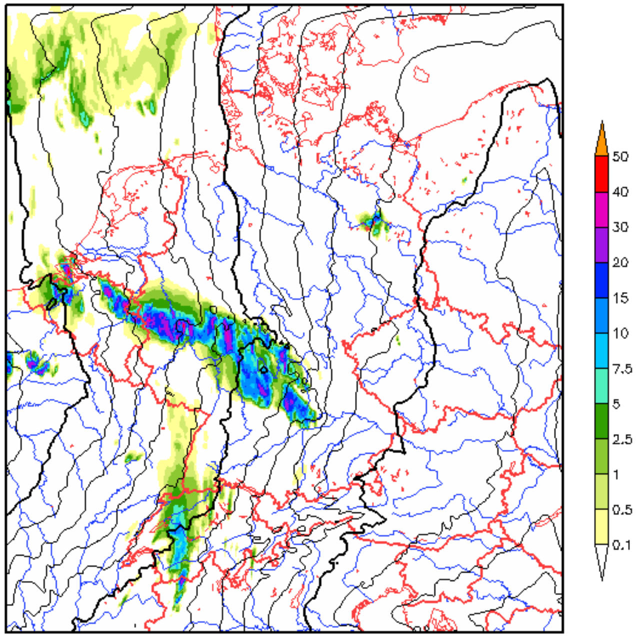


COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

‚nnew‘

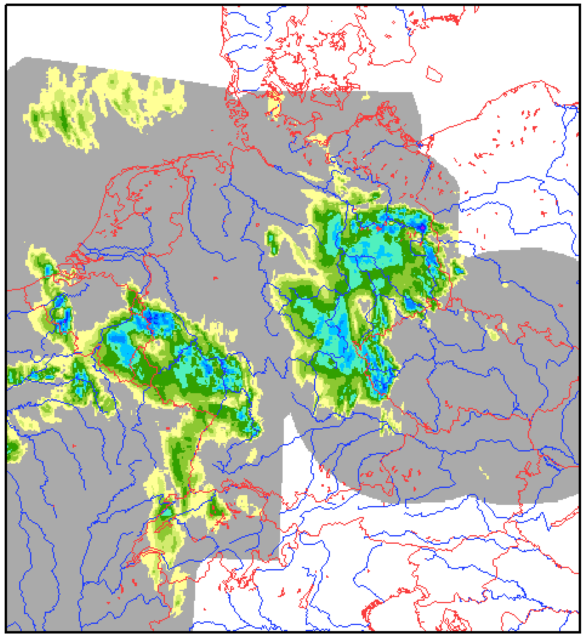
Start time: 20.06.2013 12:00 UTC 4.26r14_FW2_MF
Forecast time: 20.06.2013 21:00 UTC
Total precipitation [mm/1h] (shaded) Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



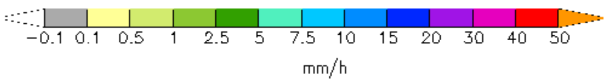
Totprec:	Mean: 0.420527	Min: 0	Max: 53.4863	Sigma: 2.22193
FI700:	Mean: 311.481	Min: 303.598	Max: 318.881	Sigma: 3.81183

Radar

RADAR COMPOSITE
valid: 20 JUN 2013 20 – 21 UTC
1h PRECIPITATION

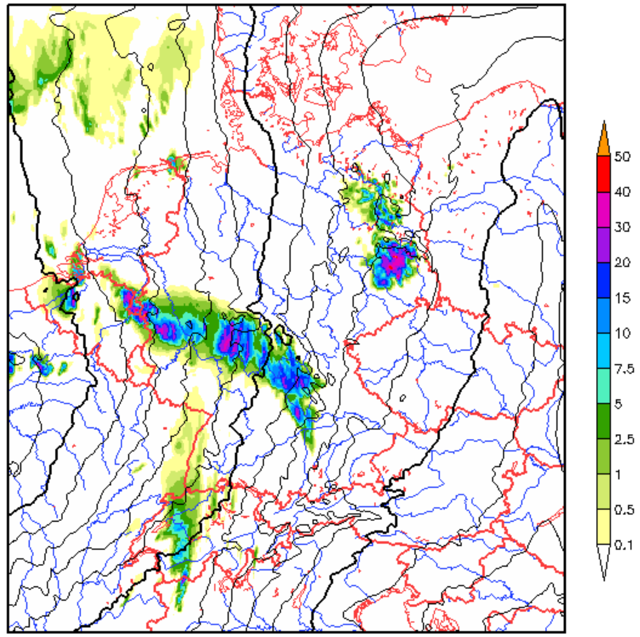


Mean: 0.736758 Min: 0 Max: 24.013



‚nnow‘

Start time: 20.06.2013 12:00 UTC 4.26r18_FW2_MF_qxnow
Forecast time: 20.06.2013 21:00 UTC
Total precipitation [mm/1h] (shaded) Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



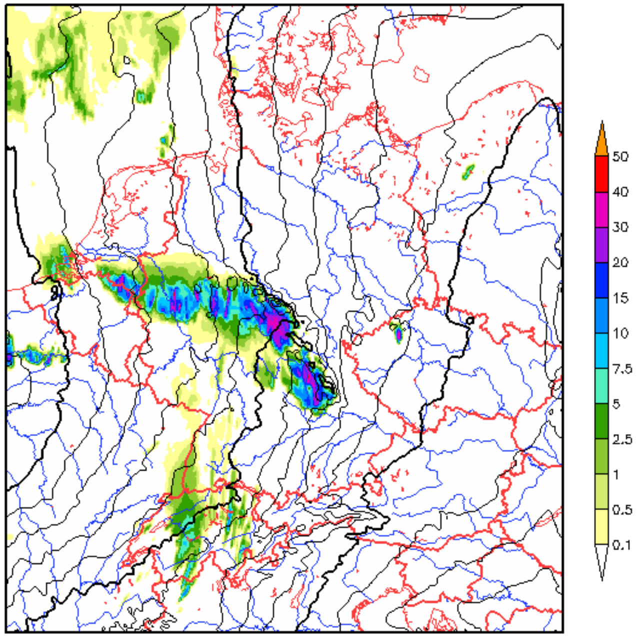
Totprec:	Mean: 0.474554	Min: 0	Max: 52.0176	Sigma: 2.45733
FI700:	Mean: 311.077	Min: 303.598	Max: 318.881	Sigma: 3.79116

COSMO-DE, 20.06.2013, 12 UTC run
1h precipitation sum

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

‚nnew‘

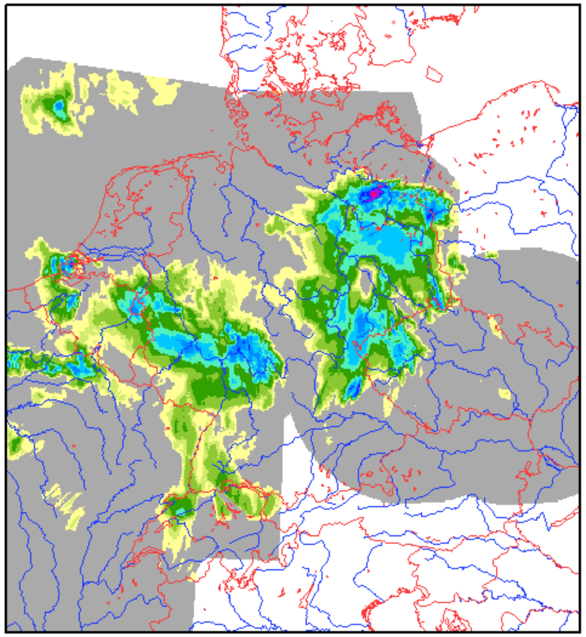
Start time: 20.06.2013 12:00 UTC 4.26r14_FW2_MF
Forecast time: 20.06.2013 22:00 UTC
Total precipitation [mm/1h] (shaded) Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



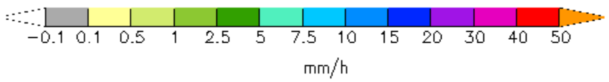
Totprec: Mean: 0.417346 Min: 0 Max: 45.7441 Sigma: 2.26247
FI700: Mean: 311.277 Min: 303.802 Max: 319.114 Sigma: 3.72163

Radar

RADAR COMPOSITE
valid: 20 JUN 2013 21 – 22 UTC
1h PRECIPITATION

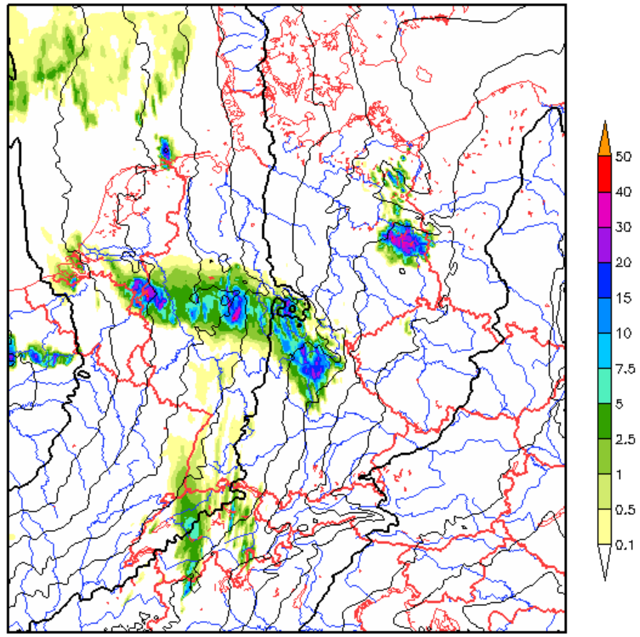


Mean: 0.93343 Min: 0 Max: 42.3395



‚nnow‘

Start time: 20.06.2013 12:00 UTC 4.26r18_FW2_MF_qxnow
Forecast time: 20.06.2013 22:00 UTC
Total precipitation [mm/1h] (shaded) Geopot. at 700 hPa [gpdm] (dist. isol. 1gpdm



Totprec: Mean: 0.405306 Min: 0 Max: 50.3535 Sigma: 2.07876
FI700: Mean: 311.064 Min: 303.782 Max: 319.114 Sigma: 3.72039

Kinetic energy spectra in COSMO/EULAG

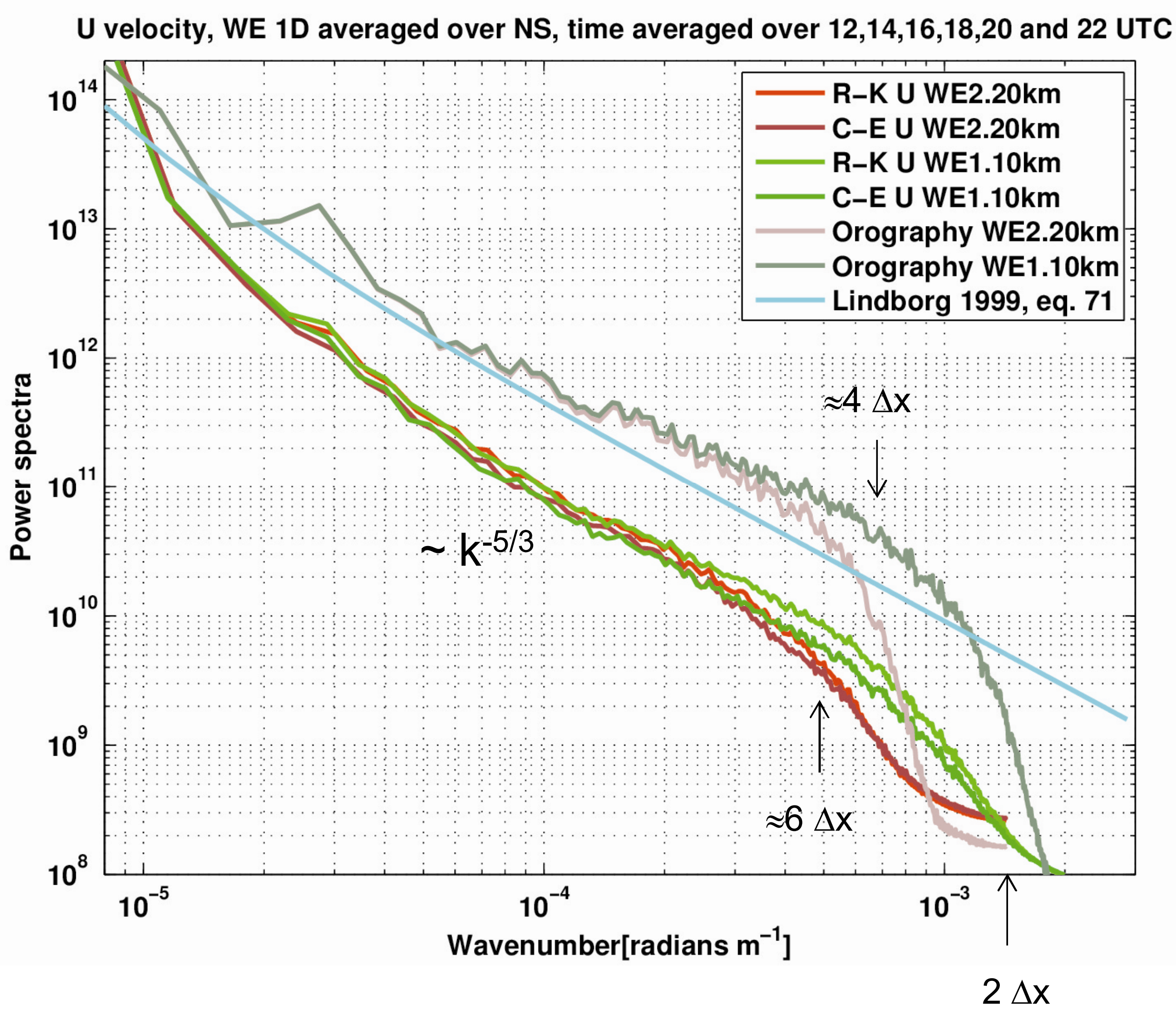
Z. Piotrowski, M. Kurowski, B. Rosa, M. Ziemianski (IMGW)

We evaluate power spectra for COSMO-EULAG and COSMO-RK at 2.2 km and 1.1 km. In addition, we examine power spectra for 0.55 km and 0.28 km COSMO-EULAG simulations on a limited domain.

Methodology follows Skamarock 2004 „Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra" paper, applied to a stable autumn period.

For the 2.2 km and 1.1 km both dynamical cores exhibit similar response to the increasing resolution.

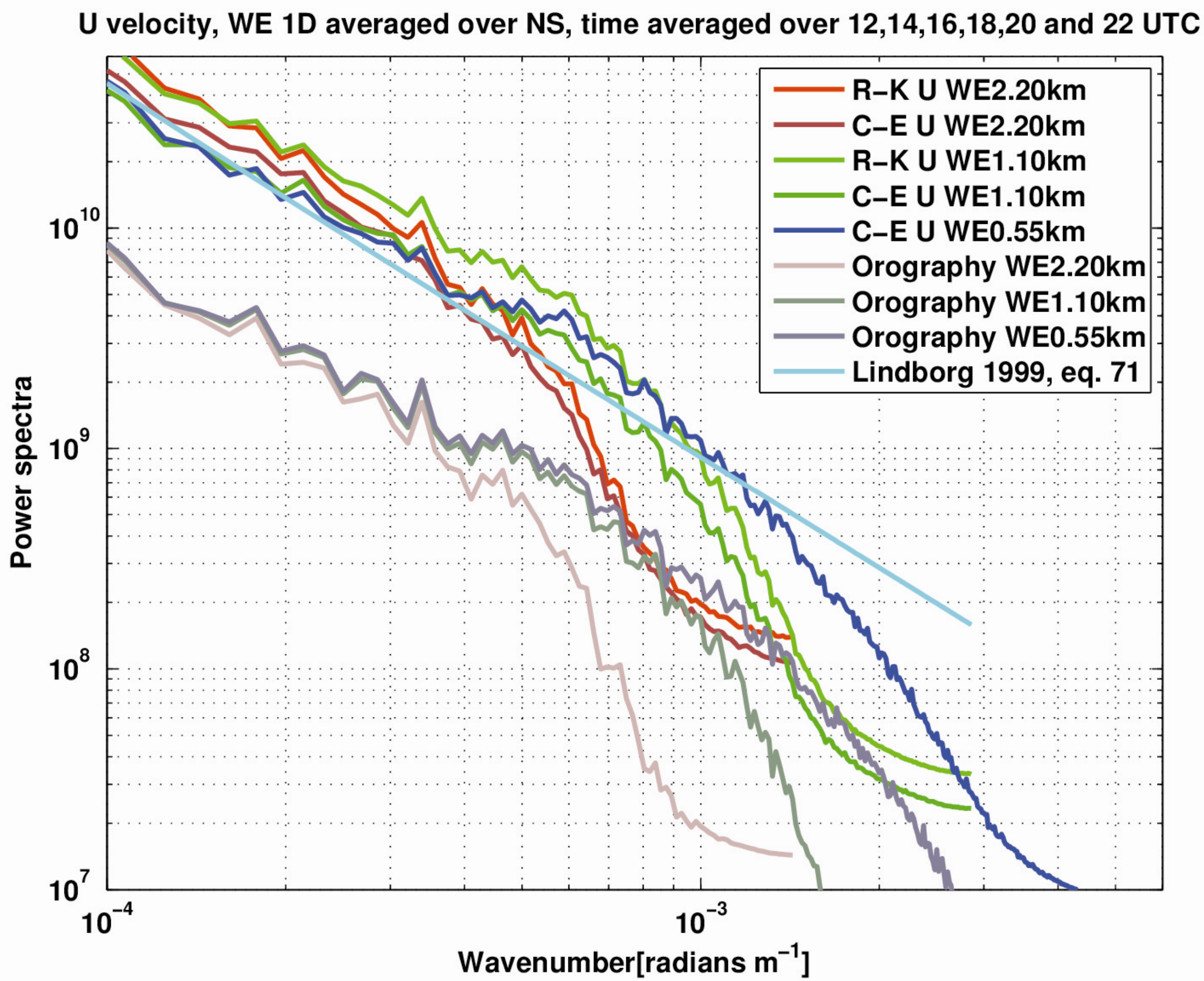
Kinetic energy spectra 2.2 km and 1.1 km



Comparision of kinetic energy spectra for CE and RK simulations of stable scenario for 26th - 36th model level above the ground.

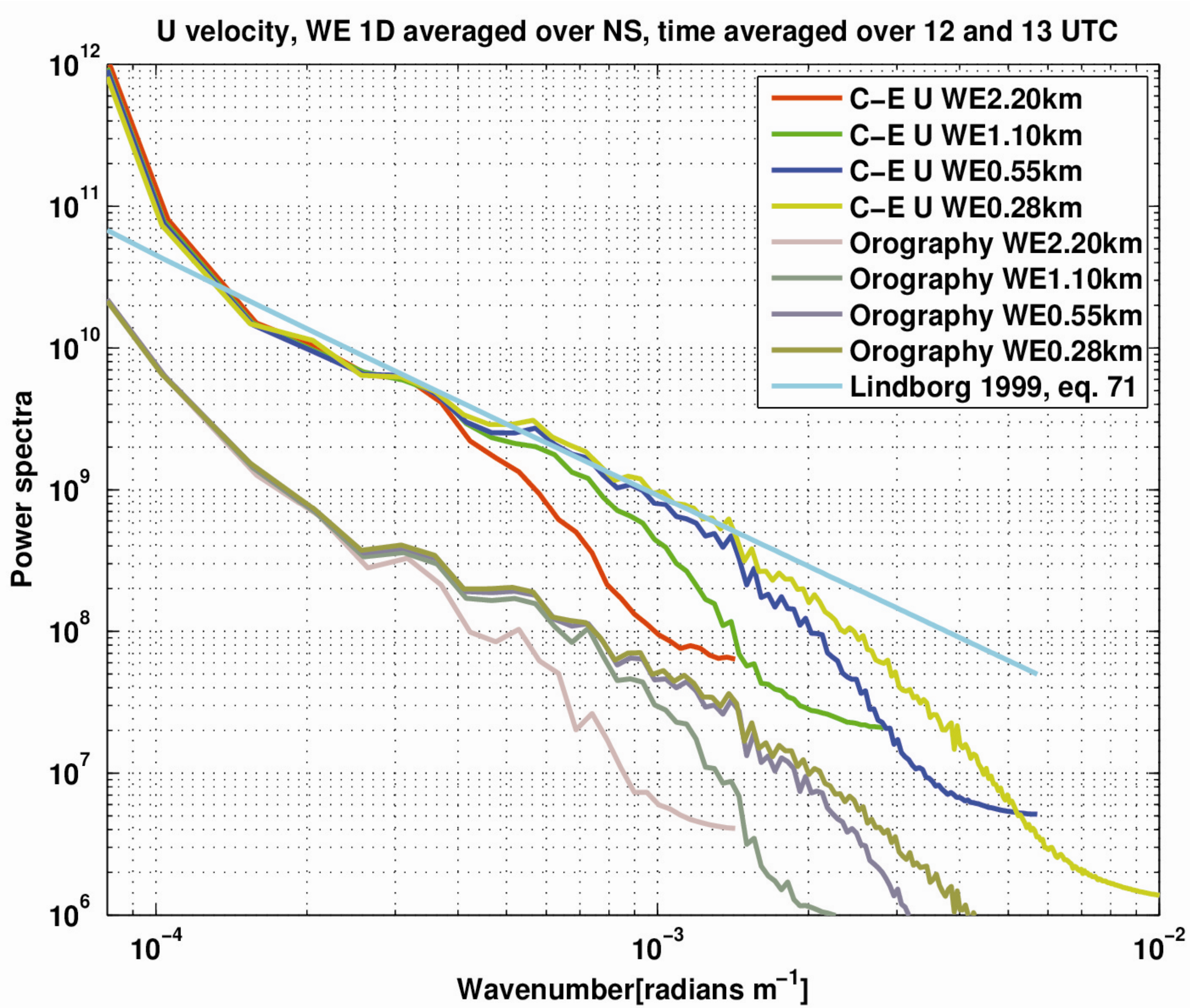
Note that spectra pairs (2.2 km red and 1.1 km green) for CE and RK compare similarily to the reference slope (blue).

Kinetic energy spectra 2.2 km, 1.1 km and 0.55 km on limited domain



Comparision of kinetic energy spectra for CE and RK simulations of stable scenario for 26th - 36th model level above the ground (only tail of the spectrum is shown)

Kinetic energy spectra 2.2 km, 1.1 km, 0.55 km and 0.28 km on limited domain



Comparision of kinetic energy spectra for CE simulations of stable scenario for 26th - 36th model level above the ground

New Bott advection operator with deformational correction

W. Schneider, A. Bott (Univ. Bonn), U. Blahak (DWD)

Currently used tracer advection scheme (*Bott (1989) MWR*) is based on operator-split 1D finite-volume operations → tendency to instability in steep terrain ← Strang-splitting increases stability (but expensive)

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Improving the time-splitting errors of one-dimensional advection schemes in multidimensional applications

Andreas Bott

Meteorological Institute University of Bonn, Germany

Bott scheme with deformational correction: basic idea

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

In the Cartesian (x_1, x_2, x_3)-coordinate system the transport equation for a substance with mass density ψ is given by

$$\frac{\partial \psi}{\partial t} = -\nabla \cdot (\psi \mathbf{v}) = -\sum_{i=1}^{3} \frac{\partial}{\partial x_i}(\psi \dot{x}_i) \tag{1}$$

In order to derive the consistent form of the advection scheme, Eq. (1) is formally rewritten as

$$\frac{\partial \psi}{\partial t} = -\sum_{i=1}^{3} \left(\frac{\partial}{\partial x_i}(\psi \dot{x}_i) - \psi \frac{\partial \dot{x}_i}{\partial x_i} \right) - \psi \nabla \cdot \mathbf{v} \tag{4}$$

Strain deformation terms
Their sum = divergence

Obviously, the second and third term on the right-hand side of this equation cancel each other. Eq. (4) is now solved by means of the following time-splitting approach

$$\begin{aligned}
\psi_1^n &= \psi_0^n - \left(F(\psi_0^n, \dot{x}_r^n) - \psi_0^n \frac{\partial \dot{x}_r^n}{\partial x_r} \Delta t \right) \\
\psi_2^n &= \psi_1^n - \left(F(\psi_1^n, \dot{x}_s^n) - \psi_0^n \frac{\partial \dot{x}_s^n}{\partial x_s} \Delta t \right) \\
\psi^{n+1} &= \psi_2^n - \left(F(\psi_2^n, \dot{x}_t^n) - \psi_0^n \frac{\partial \dot{x}_t^n}{\partial x_t} \Delta t \right) - \psi_0^n \nabla \cdot \mathbf{v} \Delta t \\
&= \psi_2^n - F(\psi_2^n, \dot{x}_t^n) - \psi_0^n \left(\frac{\partial \dot{x}_r^n}{\partial x_r} + \frac{\partial \dot{x}_s^n}{\partial x_s} \right) \Delta t
\end{aligned} \tag{5}$$

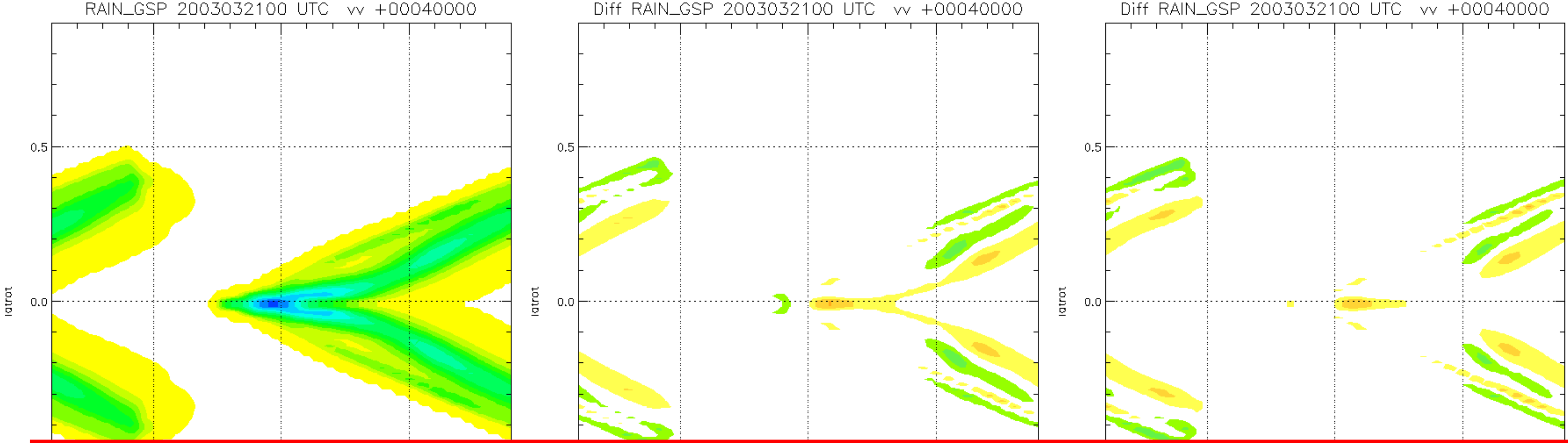
Properties:

- ➔ Exactly consistent
- ➔ Exactly conserving
- ➔ Almost shape preserving
- ➔ Positive definite
- ➔ Bonn group claims:
  - ➔ Increased stability in steep terrain
  - ➔ No need for „true strang splitting“ any more

Bott scheme with deformational correction: idealized COSMO WK82

Accumulated rain after 4 h

New Bott | Diff Bott2 – new Bott | Diff Bott2_Strang – new Bott



Current implementation:
Coupling of separate Bonn code by Werner Schneider, vectorization by Ulrich Blahak.
Good for current testing, but new implementation based on the existing COSMO routines of the Bott schemes would be desireable!

Thank you for your attention!